Modeling and Control of Contact Dynamics for a Free-Flying Space Robot in Target Capture Operation

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論　文　内　容　要　旨

As the number of satellites in orbit increases, overcrowding of the orbital environment has become a serious issue. Abandoning malfunctioning satellites wastes orbital resources. Furthermore, if such satellites drift in orbit, they would be potential hazardous to other operational satellites. Satellite collisions make a lot of new space debris and this leads to a cycle of the debris generation. In order to avoid such a situation, service and rescue missions for satellites are becoming important. As for non-contingent service to an operational satellite, refueling should be beneficial to extend mission life and replacing on-board components will be effective for future platforms. As for contingent servicing, or rescue, re-orbiting stranded and end-of-life satellites will be a primary focus. Up to now, such on-orbit servicing missions have been carried out by astronauts. In those missions, the astronauts have taken great physical risks: They were sometimes forced to dive for the target satellite without an umbilical cord. Because of the danger and expense, there are great hopes that unmanned space robots will perform such servicing missions instead of astronauts.

The Engineering Test Satellite VII (ETS-VII), 1997-1999 by NASDA, Japan, established a solid basis for the technology of autonomous rendezvous-docking and robotic operation on an unmanned satellite. Orbital Express, 2007 by DARPA, demonstrated the autonomous rendezvous-docking and refueling service successfully. However, those demonstrations were limited to the operation with a cooperative target. Here, cooperative means the existence of attitude stabilization, signal responding devices (transponders and/or optical markers), and dedicated fixtures on the target. In the above demonstrations, the targets had all of these features. Particularly, the fixtures used on the targets have special structures so that the gripper can perform a secure grasp. However, in practical future service and rescue missions, most targets are non-cooperative.

In order to capture a non-cooperative target, we need an alternative grasping point instead of prepared fixtures. There are promising substitutes: handrail-like structures, a PAF (Payload Attach Fitting), thruster nozzles and so on. The handrail-like structures allow an enveloping grasp by the gripper similar to that used in ETS-VII. But such structures are not usually mounted on commercial satellites. The PAF is a good candidate in terms of mechanical strength. But an enveloping grasp will not be achieved. The nozzle cone is also a good candidate in terms of commonality in GEO satellites. However, nozzle cones may not be strong enough for the impact against the capturing device. Also, an enveloping grasp will not be achieved. In the case of non-enveloping grasp, the gripper can potentially push the target away during the sequence of the capture. An effective control method should be developed to prevent the target from being pushed off and to maintain contact until the capture is completed. Even ``cooperative" targets may involve unforeseen contact where the influence on end point positioning or arm configuration must be minimized. In the case that the targets for the service are space stations or other large space structures, these structures are considered as immobile targets, yet the robot itself must be controlled to avoid bounce-off. Vision-based manipulation is a promising solution that a lot of researchers are tackling. The manipulator is controlled to avoid contact and to maintain zero relative velocity to the target. However, this method requires many sensors and the control system is complicated in general. Hence the contact phenomena itself should be clarified and controlled with as simple a method as possible.

This dissertation addresses modeling and control of the contact dynamics for a free-flying space robot in a target capture operation. In order to realize the secure contact in capture of a non-cooperative satellite, this research clarifies the following issues: 1) the contact dynamics of a free-flying robot and a target, 2) the dynamic condition to prevent pushing the target at the initial contact, 3) the appropriate impedance control strategy to realize the condition, 4) the experimental verification for the proposed satellite capture strategy.

First of all, the chaser robot with a manipulator is modeled as a mechanical impedance system consisting of masses, dampers and springs. Combining with the target dynamics through a conventional contact model, the whole capture dynamics model is represented as a coupled vibration system. A contact experiment with an air-floating testbed was conducted for evaluating the relationship between the model parameter and the dynamic characteristics. Furthermore, the author proposes a determination method for contact parameters with a hybrid simulator. The control time delay of the hybrid simulator was evaluated and modeled. The contact parameters were obtained successfully by comparing between the result of the hybrid simulation and the one of a numerical simulation with the time delay model.

Using the dynamics model, the dissertation clarifies the relationship between the impedance characteristics and the contact motion of the target. In order to evaluate the relationship two evaluation indexes were defined.

The restitution coefficient was redefined as ``Restitution Coefficient of Impedance (RCI)" so as to include the effect of the viscosity and stiffness in the contact of the impedance system. The theoretical formulation reveals that the restitution coefficient is obtained by the equations of motion for the proposed two-body contact model. This dissertation represents the post-contact target motion with the RCI. The equilibrium point of the manipulator impedance is defined as a reference point. When the RCI is equal to zero, the target comes to a stop at the reference point right after the initial contact. When the RCI is smaller than zero, the target continues to move in the same direction as initial motion after contact. The target pushes the manipulator to inside of the reference point. When the RCI is larger than zero, the target rebounds off the manipulator and moves in the opposite direction of the initial motion.

The ``Virtual Mass of Impedance System (VMI)" model is also defined as another evaluation index of the target's post-contact motion. This model projects the impedance characteristics to a mass property. The virtual mass makes the contact problem simpler.

The virtual mass explains the target motion in post-contact from the view point of kinetic energy. When the RCI is equal to zero, all of the kinetic energy of the target is transferred to the manipulator. This phenomenon occurs when the VMI is equal to the target mass under a perfectly elastic collision. This dissertation defines the phenomenon as "Impedance Matching. When the manipulator impedance gives a lower VMI than the matching condition, the target loses its kinetic energy a little bit on each contact and comes to a stop after several contacts. On the other hand, when the manipulator impedance gives a larger VMI than the matching condition, the kinetic energy is reflected to the target. In this case, the target rebounds from the manipulator and gets away. Therefore, this dissertation concludes the condition of secure contact as "the manipulator impedance gives the matching or smaller VMI." The combinations of impedance characteristics which satisfy the above the condition are numerous. Hence, a determination method of appropriate impedance condition is also clarified based on the vibration properties of the manipulator and a magnification ratio.

The control method of the hand impedance is the next issue. Various impedance control methods for manipulator on the ground were proposed by former researchers. Since space robots do not have a fixed base, contact and reaction of the arm motion results in translation and/or rotation of the robot. In conventional methods, the impedance control is interfered with the inertial properties of the floating base. So the desired end-effector impedance is not easy to attain. This interference varies with the arm configuration, so even a simple operation such as extending the manipulator arm results in inaccurate impedance at the end-effector. In this thesis, a novel impedance control method for a free-flying space robot is discussed. The motion of the manipulator end-effector is controlled independently of the base motion with respect to inertial coordinates by joint torques or velocity. This method requires only a Force/Torque Sensor in the wrist of the manipulator. Arbitrary impedance characteristics were achieved by the proposed control method regardless of the inherent impedance properties of the robot. It was also demonstrated that even larger (more massive) impedance than the real properties of the robot could be stably achieved. A satellite capture mission and a surface inspection mission of a large space structure are discussed as practical applications. A free-flying robot can maintain stable contact with a free-flying target and the surface of a stationary structure by using the proposed method. In these examples, the operator is only required to execute a command to extend the manipulator toward the target with arbitrary impedance properties. The proposed method will provide a solid basis for capture and contact operations in future orbital servicing missions by free-flying space robots. Contact experiments with a real robot manipulator and an air-floating testbed were conducted to verify the proposed contact control theory. Through the experiments, the manipulator under an impedance control was demonstrated to maintain the contact with a free-floating object. In addition, the relation between the impedance characteristic and the contact motion is analyzed experimentally. The viscosity factor of impedance makes a large contact force. In contrast, the stiffness factor does not have not significant influence on the contact.

In practical capture missions, the chaser manipulator has the problem of control time delay. Particularly, space robots have lower performance than common robots on the ground in general because the reliability has priority over the performance. The delay makes the contact maintenance difficult because it increases the total impulse of the contact. The influence of the time delay on the contact is also clarified through the experiment. The influence of the viscosity and time delay are affected by the contact stiffness. A larger contact stiffness makes the influence of the viscosity smaller and, the influence of the time delay larger. The control time delay makes the impact increase, because the specific structural impedance of the manipulator arm dominates instead of the controlled impedance under the delay time. In the case of the time delay exists, the RCI and VMI are represented as a time averages of those from structural impedance and control impedance. Comparing the waveform, the effect of delay time increase was similar to the effect of impedance increase.

Finally, the satellite capture experiment using a hybrid simulator is conducted. When the verification target has a large body or complicated structure, the hybrid simulator is useful. Two robots emulated the motions of a chaser and a target satellite. Through the contact experiments, the concept of the proposed method of contact maintenance with impedance control was verified. The time delay influence on the apparent impedance is also identified. Then a promising capture strategy for non-cooperative target using a nozzle cone of a target was verified. A capture probe is inserted into the thruster nozzle of a target satellite, and the end of the probe is expanded inside the combustion chamber for firm grasp. In this strategy, the nozzle skirt is useful to guide the probe insertion. However, the chaser can push the target away during open contact with the skirt, and nozzles are usually fragile, even though the combustion chamber can withstand enough load. Therefore, the contact forces should be minimized during the probe insertion. In order to clarify the contact between the nozzle skirt and the manipulator, an apparent mass theory is applied. Using the apparent mass of the contact point, the matching condition is calculated. It was clearly demonstrated that if the magnitude of the impedance is equal to or lower than that of impedance matching, stable contact and insertion is performed. In contrast, if the impedance is larger than that of impedance matching, the target is hit by the probe and subsequently pushed away from the reach of the probe. Through these experiments, the author confirms that the proposed capture control method is effective for the satellite capture operation.

論文審査結果の要旨

軌道上を自由飛行するいわゆるフリーフライングロボットによる故障衛星の捕獲作業は，ミッション終了後の人工衛星が宇宙ゴミとなることを防止する手段として期待されているが，これを実現するためには，軌道上で対象衛星を突き飛ばすことなく，安全に捕獲する制御技術の確立が必要である。本論文は，フリーフライング宇宙ロボットによる衛星捕獲時の衝突力学を定式化し，安定して接触を維持するための条件と制御法を機械インピーダンスの概念を用いて論じたものであり，全編 7 章よりなる。

第 1 章は序論であり，本研究の背景および目的を述べている。

第 2 章では，フリーフライング宇宙ロボットの動力学，および衛星捕獲の衝突力学の定式化について示し，本研究で用いるインピーダンスモデル，およびそのパラメータの同定について述べている。

第 3 章では，衝突後の対象衛星の運動を定式化し，インピーダンス条件により運動が 3 種類に分類できることを明らかにしている。また，ロボットハンドが衛星に接触する際の衝撃力を評価する指標として Virtual Mass of Impedance System (VMI) を提案し，同指標を用いて衝突後の接触維持を可能とするインピーダンス・マッチングの条件を導いている。これらはいずれも新しい概念の提案であり，重要な成果である。

第 4 章では，フリーフライング宇宙ロボットにおけるインピーダンス制御法について論じている。慣性系から見たロボットハンドのインピーダンス特性を，任意に与える制御手法を提案し，その有効性を数値シミュレーションにより検証している。これは有用な成果である。

第 5 章では，空気浮上実験装置および大型振り子により微小重力環境を模擬した衝突実験について示し，インピーダンス条件の違いによる衝突後の運動の違いを実験により検証している。また，ロボットアームの制御に時間遅れがある場合には，上に定義した VMI 値が遅れ時間に応じて増加し，マッチング条件が変化することを定量的に評価している。これは有用な成果である。

第 6 章では，実際の衛星捕獲作業を模擬した検証実験について示している。人工衛星のスラスタノズルにロボットハンドを挿入し内側から固定する手法において，ノズル表面との接触維持条件を満たすインピーダンス制御を行うことにより，ノズルを突き飛ばすことなく表面をなぞりながら最深部へ到達可能であることを，実験により検証している。これは，有益な成果である。

第 7 章は結論である。

以上要するに，本論文は，フリーフライング宇宙ロボットによる衛星捕獲の際の衝突力学を明らかにし，接触を維持するための条件について新たに評価指標を提案し，ロボットハンドに適切なインピーダンス制御を行うことにより安全に捕獲を行う手法を開発し，シミュレーションおよび実験によりその有効性を確認したものであり，航空宇宙工学および宇宙探査工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。